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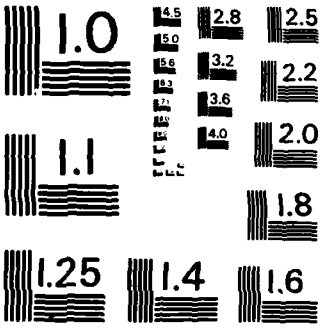

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The HF propagation channel is characterized by its inextricable relationship to the ionospheric medium; and because the medium is variable in both space and time, the channel is itself a temporally and spatially-varying entity. The nature of the channel has been the subject of continuous investigation over the years and models of propagation effects have been developed to assist in communication system design and in operational frequency management. HF communication

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20. ABSTRACT (Continued)

system sensitivity to ionospheric disturbances is well known and the role of the benign ionosphere in affecting efficient skywave communication is acknowledged.

In the electronic warfare arena it is desired to reduce or prevent the use of HF by the enemy while at the same time to retain its use by friendly forces. It is suggested that the "conveniences" provided by ionospheric specification support in the unstressed environment may become of major significance in the EW environment. Precise, timely, and affordable ionospheric specification will, in principle, facilitate the implementation of tactics for efficient jamming of an enemy or for avoiding such a threat. Nevertheless, it is clear that application of this technique requires exceedingly accurate channel specification over geographical zones of interest. Imprecision may actually result in an inadvertent impairment in the capability of friendly forces to conduct electronic warfare successfully. In short, application of strictly climatological prediction techniques should be suppressed in favor of prediction techniques based upon near-real time channel assessment.

NRL is investigating various remote sensing schemes including terrestrial-oblique and satellite-borne ionosonde to serve as update tools in the specification of the ionosphere. It has been shown by NRL tests that ionospheric specifications using these tools may be useful over an extended geographical zone. Furthermore, temporal extrapolation (i.e., forecasting) may be satisfactory for up to 24 hours provided the forecast is not obviated by unexpected intense solar and magnetic activity.

Following identification of certain well known propagation principles, this paper outlines how quasi-real time propagation data may be utilized to engage in operationally-viable propagation tactics.

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THE ROLE OF THE PROPAGATION ENVIRONMENT IN HF ELECTRONIC WARFARE

1.0 Introduction

One of the virtues of the HF channel for BLOS application is that it is dependent upon a "satellite which doesn't fall down"; namely, the ionosphere. This virtue has led to a rediscovery of the HF band for communications following at least a decade of neglect as a result of an exaggerated emphasis upon satellite solutions to a variety of communications requirements. One of the principal reasons given for directing major DoD emphasis toward SATCOM was that HF, the primary long haul communication band prior to the advent of the space age, was unreliable and uncooperative. This was because the ionosphere itself was viewed as unreliable and uncooperative. A number of factors have contributed to the rediscovery of HF and they include:

- relatively low cost
- survivability and endurance in a nuclear environment
- substantial current hardware inventory at HF
- improved propagation prediction
- improved quasi-real time channel assessment schemes
- development of robust (non-MUF seeking) communication systems
- development of improved networking schemes to mitigate against ionospheric effects
- development of advanced modems and adaptive antenna concepts

A majority of the factors listed above fall into the general category of "adaptive HF". This term is somewhat imprecise and controversial but nevertheless approaches to Adaptive HF all suggest that the ionospheric vagaries are circumvented in some way.

The central theme of this paper is directed toward an elucidation of those adaptive HF schemes which are not intrinsicly robust to jamming or signal intercept but achieve robustness through precise information about the channel.

2.0 Statement of the Problem

In peacetime, there are a number of possibilities for achieving (and improving) link connectivity at HF. During stressed conditions (both political and environmental), issues of communication security and operation against a jamming threat may arise. This situation may become even more acute during nuclear engagements. It is essential that systems operate successfully in this harrassed environment and the approach outlined herein identifies precise channel assessment as one of a possible set of solutions. The successful jamming of unfriendly assets involves similar principles. The viability of propagation related ECCM and ECM techniques is dependent upon a systems approach. The principles are well known and understood. The problem is one of credibility since it is unclear that the state-of-the-art in forecasting/assessment is sufficiently advanced to allow application of propagation tactics.

3.0 Propagation Tactics

Clearly, if the propagation channel could be precisely specified in advance for arbitrary HF links, there would be a minimization in the complexity of HF research and of frequency management requirements. If the channel characterization were quasi-deterministic and complete, then for any specified HF link, one should be able to specify all possible propagation modes in terms of signal properties such as fading rate and depth, absorption, multipath spread, and doppler properties. Given, as well, a precise characterization of the noise (atmospheric, man-made, and galactic) across the HF band, signal-to-noise information would be available for determination of

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the performance of arbitrary HF systems which exist in this ideally-specified environment. If a remote enemy jammer can be forced to operate in a channel environment more subject to fading than the wanted signal, then the potential capacity to disable or distort communication connectivity would be reduced. It should also be possible to develop a network of nodes such that the optimum transmission frequencies are greater than those for a specified enemy sky-wave jammer. Enemy ground-wave jammers can be circumvented by employing sky-wave communication combined with polarization tactics. Naturally, similar arguments may be applied in the reverse situation. There are a plethora of operational scenarios which could be developed, most of which are obvious.

As indicated above the key to successful use of propagation tactics is accurate specification of the HF channel, or more precisely the ionospheric sub-channel in the region of interest. Statistical models - however elegant - will not suffice for this purpose. Indeed, it is possible to show that a statistical approach applied in an operational setting may, under certain conditions, create more vulnerabilities than robust "propagation-blind" techniques currently admit. It is certainly necessary to use statistical representations of the HF channel environment, including models of ground-wave and sky-wave propagation and noise, to deduce the potential susceptability of various systems - ashore, afloat, and in the air - to a jamming threat. One purpose of this type of analysis should be to provide a general awareness of the propagation problem and to identify a set of simple countermeasures which may be applied in the absence of real-time channel specification. Statistical models, in this case, may be utilized to specify (or limit) the range of conditions over which a system operating under a jamming threat must be designed to adapt. Again, the reverse situation for which an optimized jammer design is to be developed, admits to a similar justification for climatological modelling.

Hayden [1979] has prepared perhaps the most comprehensive treatment of HF propagation factors in connection with jamming which has appeared in the open literature. This report is recommended to all propagation specialists who wish to achieve a basic understanding of the propagation environment at HF. The following motivational statement due to Dr. Hayden is reprinted below:

> "The HF portion of the electromagnetic spectrum (2-32 MHz....)provides channels for a variety of useful communication services. The characteristics of communication systems in this range of frequencies are adaptable to provision of services from large moving platforms. Under favorable circumstances, terminal equipment requirements are modest, and ranges from line-of-sight to several thousands of kilometers are possible. The practice of jamming communication services in the HF part of the spectrum must cope with a complexity of wave propagation phenomena not experienced at higher frequencies. This document is designed to illuminate both the nature of the wave propagation phenomena and their impact on planning and execution of a jamming operation. Its purpose is to enhance the ability to cope. A systematic basis is presented for understanding and, ultimately, for estimating the impact of HF wave propagation phenomena on jamming signal delivery...."

The ability "to cope" is certainly necessary but it is conceivable that quasi-real time channel assessment may lead to a truly operational game plan for utilization of propagation tactics. With availability of remote sensing devices to sound the ionospheric channel (either vertically or obliquely) and

with the efficient application of mini- and micro- computer technology, the potential for development of a believable system is not insignificant. Its realization only awaits the resolve of the sponsor community to design appropriate tests for establishment of validity limits and to structure a program which is affordable.

4.0 The Ionospheric Sub-Channel of the HF Propagation Link

4.1 Ionospheric Modelling

The ionosphere and the radiowave propagation environment with which it is associated have been the subject of intensive research over the years. As long as ionospheric modelling has existed, there have been attempts to model its behavior. A recent review of progress in development of ionospheric modelling has been given by Westerlund [1981] and progress in the area of ionospheric predictions has been provided by Davies [1981]. Nisbet [1978] has reviewed the benefits which accrue from operational physical models of the ionosphere and Kohnlein [1978] has examined electron density models. Bradley [1979a, 1979b] has examined the modelling needs at MF and HF for both long and short-term requirements. In addition, a review of ionospheric and radiowave propagation models has been initiated by Goodman, [1982].

4.2 Radiowave Propagation Modelling at HF

There are a host of ionospheric models, some of which may have application in a propagation forecasting scenario, but in view of space constraints a review of these models is hereby suppressed and only propagation models are considered.

The most noteworthy general HF propagation models employed in the U.S. to assist in the design and operation of HF telecommunication systems have been developed by ITS-Boulder, although contributions from a variety of research organizations - both U.S. and foreign - have led to these models. The models referred to are ITS-78 and IONCAP, although the latter has not yet been fully documented. Below is a partial listing of models together with their code names and originators if available.

TABLE 1

List of HF Propagation Models

MODEL NAME (Abbreviated)	CODE NAME	DEVELOPER*
HF Comm. Assessment Mod.	HFCAM	ECAC
HF Max. Usable Freq. Eval.	HFMUFES-3/4	ITS
Ionos. Comm. Anal. & Pred. Prog.	IONCAP	ITS
Mini-computer Mod. for MUF Pred.in HF Comm	MINIMUF	NOSC
Quiet-time LUF	QLOF	NOSC
Sudden Ionos. Dist. Grid	SIDGRID	NOSC
HF Sky-wave Prop. Mod.	SKYWAVE	ITS
X-Ray Flare & SWF Duration Mod.	XRAY FLARE	NOSC
Mod for est. MUF/FOT by CCIR Proc.	MUFFY	AL
CCIR Field Strength Mod.	HFMLOSS	CCIR & RIMIA
Mod. for est. Sys. Perf.Parameters	APPLAB	AL

* ECAC Electromagnetic Compatibility and Analysis Center, DOD/USA
ITS Institute for Telecommunication Sciences, DOC/USA
NOSC Naval Oceanographic Systems Center, DoD-USN/USA
CCIR International Radio Consultative Committee/ITU
AL Appleton Laboratory - Slough/U.K.

4.3 Model Utilization

NRL Code 4180 (Ionospheric Effects Branch) has been involved in the process of identifying models which would be suitable for FLEET use in HF communication frequency management. Physical and empirical models of the ionosphere have been examined. The most exploitable ionospheric model amenable to mini-computer technology would appear to be a combination of a model due to Ching and Chiu [1973] for the bottomside and Bent et al [1975] for the topside. In addition to the fact that these models are fundamentally ionospheric in nature, rather than tailored propagation models, the suitability of the results over vast oceanic regions of interest to the U.S. Navy is subject to some question. Accordingly, NRL 4180 examined other models which could be applied more immediately in an update mode using auxiliary data obtained from a variety of sensors. NRL, being a U.S. Navy organization, logically reviewed the efforts of NOSC for this purpose. The NOSC program MINIMUF has proved to be quite useful as an algorithm for extrapolating real-time sounder data both in space and time, and much of the analysis to date has employed this model. In view of the success achieved using MINIMUF, NRL 4180 is now examining the efficacy of utilizing IONCAP, albeit in a skeletized form, for the purposes of HF propagation assessment.

4.4 Some Comments on Radiowave Propagation Prediction at HF

Propagation prediction services have been provided by the U.S. Department of Commerce since the formation of the Interservice Radio Propagation Laboratory (IRPL) in 1942. It subsequently was known as the Central Radio Propagation Laboratory (CRPL) and at present is associated with the Space Environment Laboratory (SEL) of NOAA. Certain services of the Space Environment Services Center (SESC) at SEL are joint with the Air Weather Service (AWS) of the US Air Force. The Laboratory also runs an interactive computer system (updated in real-time) for direct access to qualified users.

Geophysical forecasting and ionospheric modelling studies at the U.S.A.F. Global Weather Central (GWC) of the Air Weather Service have been detailed by Thompson and Secan [1979] and Tascione et al [1979]. HF propagation forecasts are performed and transmitted to qualified users routinely.

Forecasting and prediction services are of course, performed outside the U.S. as well. For information on these services and techniques refer to Donnelly [1979].

Radiowave prediction services are useful in a number of applications and perhaps even in planning for some military exercises; however for utilization in real time propagation tactics, these services are of limited value. The reason for this is clearly because the use of propagation tactics may be a matter of life or death. The ability to predict solar flares is not well developed at present and therefore Sudden Ionospheric Disturbance (SID) events such as Short Wave Fades (SWF) occur over the sunlit hemisphere without warning except for alerts delineating certain tendencies. Thus, it is not generally possible to utilize future SWF's to any tactical advantage. (A possible exception would be a large SWF lasting approximately an hour. In this case one would have sufficient time to take greater advantage of an enemy sky-wave jammer located on the sunlit side of the terminator if the friendly communication system were largely in darkness.) Forecasts of HF disturbances which are based upon observations of the disturbance sources and which provide some operationally significant lead-times, obviously have greater value. These include polar cap absorption events, snd ionospheric storm-related phenomena. The ability to forecast these phenomena depends upon accurate

assessment of the complex behavior of solar eruptions, and a detailed evaluation of the helospheric/magnetospheric/ionospheric system including the solar wind and the interplanetary magnetic field. Considerable progress has been made in this area however, only incremental improvements in HF predictions are anticipated before the end of the century.

In conclusion we find that there are only a few applications where "traditional" radiowave propagation predictions can be used operationally. This is principally because of the credibility of the predictions which are currently of insufficient accuracy. Another factor is the cost of such prediction systems which typically include extensive space and terrestrial segments and a vast data communication network....all soft and unreliable in the case of conventional and certainly nuclear conflict. Thus utility, affordability, and vulnerability arguments currently preclude the use of "traditional" prediction schemes for indirect specifications of the HF channel and for use in propagation tactics.

The alternative to prediction for indirect HF channel specification is direct specification of the channel by sounding over fixed paths and extrapolation in space and time using appropriate models. The questions then become....how accurate is this approach, what are the temporal and spatial perishabilities (i.e., decorrelation time and distance) of the specification, how would the system be configured, and at what cost?

5.0. Propagation Tactics

The goal of this section is to discuss propagation tactics, albeit superficially, and outline a set of propagation principles which may be applied in the electronic warfare area. A guiding set of principles may be utilized to achieve a certain degree of robustness for jam avoidance and/or for disrupting an enemy C^3I system. Proper use of propagation tactics is considered to be a valid adaptive HF technique. The study of propagation tactics has been pursued by others [e.g., Hayden, 1979; Argo and Rothmuller, 1981, and Rose, 1982].

The general principles to be applied are fairly easy to elucidate if propagation conditions are specified and there is no (or little) concern about uncontrolled emissions (i.e., jammers) or covert listeners (i.e., interceptors). If these conditions are specified the problem is tractable, although nuclear environmental constraints may pose serious problems due primarily to an inadequate data base. It is remarked that models for the nuclear-stressed environment may be developed using simulated events based upon natural disturbances such as flare-related SID, PCA events, ionospheric storms, and auroral forms. It is understood that certain tests of this type are being pursued using a test bed in the auroral zone [Crowley, 1981].

It is important always to remember that the potential of HF propagation tactics based upon environmental (channel) assessment to meet the requirements of the EW, SIGINT, and COMSEC communities depends heavily upon the accuracy and above-all the believability of the propagation channel information used. The goals of covert channel establishment and the capability to engage in covert and overt electronic warfare place very stringent requirements upon the ultimate system for channel assessment. A certain mythology has developed regarding the efficacy of propagation tactics in an active operational arena. The medium has been viewed as too variable for precise specification, and the scientific community - being trained to be a properly conservative entity - has inadvertantly promulgated this myth. It is the view of the present authors that many situations exist for which the intrinsic ionospheric

variability may be specified quite adequately over limited temporal and spatial domains. The specification of these domains for requisite mission objectives is the pacing item.

5.1 The Jamming Problem

The objective of jamming is to deny communication, radar coverage, or navigation services to the intended customer and the process requires delivery of a spurious or unwanted "load" to the recipient. To do this, it is important to design the jamming signal appropriately and finally to deliver it. This latter factor presumes an assessment of the propagation medium since the jammer is usually remote from the intended victim.

There are certain geometrical situations which preclude or limit the efficient delivery of jamming signals. An a-priori knowledge of these situations is of fundamental value to friend and foe alike. It is assumed that the figure-of-merit for successful jamming, for example, is to be based upon the likelihood that the ratio of spurious jammer power to (desired) signal power is the order of unity. Clearly there are cases where a $J/S \leq 1$ may incapacitate the victim and other cases where a $J/S \geq 1$ may be necessary.

5.2 Propagation Effects which Impact on Skywave Jamming: the Fading Problem

Two well known factors which relate to the efficiency (or duty cycle) of jamming include polarization fading and multipath fading. The former category of fading - usually of the Faraday rotation variety - is usually slow. This type of fading will occur even under favorably specified geometrical conditions. It is most pronounced at lower frequencies, however, owing to the f^{-2} dependence for Faraday rotation. The latter category, due to interference of several multi-path modes, may be relatively fast. If the jammer is required to deliver a spurious load at a frequency where multi-path fading is encountered, then a single jammer cannot guarantee an efficient disruption of the targeted system. Suitably-placed multiple jammers may be required. The same procedure could also be used to increase efficiency of skywave jamming in the presence of Faraday (slow) fading but the decorrelation distances are greater in this case. Another technique - but perhaps not practical - is to jam with circular (generally elliptical) polarization.

5.3 Jammer Location

Jammers may be placed on mobile platforms such as ships, aircraft and surface vehicles or at fixed shore-based facilities. They could also be placed on missiles, satellites, or at quasi-stationary sites (buoys).

There are several considerations concerning the selection of an optimum platform for jammers. First the designer (architect) should consider the sophistication of the intended victim. This relates to the frequency set available to the intended victim (a communicator, for example) as well as his flexibility in frequency management. It also includes a knowledge of the adaptive HF technologies which must be thwarted. Secondly, the designer must consider the requirement for on-station time. Next, considering the mission objective, he must determine the required power and antenna configuration. Finally, he must consider his own capability to exploit the propagation environment. This relates possibly to the existence of adequate computational capability aboard the platform housing the jammer as well as a "process" by which channel evaluation may be performed in real-time. This "process" may include on-board channel sensing capabilities or a data link over which necessary information is received from remotely-located sensors.

5.4 Shipboard Jamming: The Navy Case

In the Navy case, there are three categories of traffic to consider: ship-to-shore, shore-to-ship, and ship-to-ship. If a jammer is located aboard a ship itself, it is presumed that the shipboard jammer may position itself such that only surface wave is needed to jam the intended shipboard recipient. Therefore skywave jamming need only be considered for the case of ship-to-shore traffic. However as we shall see the process of ground-wave jamming may be disadvantageous in the shore-to-ship communication scenario.

5.4.1 Shore-to-Ship

In the shore-to-ship communication case, the shore-based transmitter will ordinarily use skywave since the groundwave path is too severely attenuated over intended operational path lengths. Since skywave is used, the link will suffer the usual absorption losses, skip defocussing losses, and divergence losses. Also, if multiple hops are required for connectivity, there will be additional sea reflection losses and the total losses associated with the skywave path are doubled for each hop. However, the situation for the communicator is not totally negative as far as vulnerability to the ship-board jammer is concerned. In fact, since the skywave signal polarization is essentially random (and may be regarded as horizontal 50% of the time) there will be a problem in jamming the link with groundwave since horizontal polarization of the ground wave mode is severely attenuated. Groundwave jamming could be presumed to be successful with a duty cycle of 0.5 under the assumption that vertical polarization is received 50% of the time.

5.4.2 Ship-to-Shore

In the ship-to-shore communication case, skywave jamming is required since groundwave modes are unavailable due to attenuation of both polarizations over anticipated BLOS distances. The jammer, to assure flexibility, requires a condition such that its MUF is greater than that associated with the target communication link. If this condition were not assured, then the communicator could simply operate above the jammer MUF (but below his own) as an effective countermeasure. Generally speaking, smaller solar zenith angles imply greater MUFS, especially for F1 and E hop modes, although variations do occur. Thus the jammer should endeavor to be in a location such that the sun is higher. Between sunrise and mid-afternoon at mid-latitudes the MUF for F2 modes is roughly monotonically increasing; between mid-afternoon and sunrise it is roughly a decreasing function. In addition MUF's generally increase in the equatorward direction. Therefore at northern mid-latitudes, the daytime jammer would best be located at a position to the southeast of the ship whose transmissions are to be jammed. The nightime jammer should be located to the southwest. Greater ranges also imply larger MUF's. Thus the jammer should be at a greater ground range from the shore site (to be jammed) than the ship-to-shore distance. This dual recommendation would generally insure higher MUF's by virtue of the higher critical frequencies encountered over the jammer-to-victim path as well as greater ranges encountered. There are, however, greater range spreading losses over the jammer-to-shore path than on the ship-to-shore communication path.

5.4.3 Ship-to-Ship

In the ship-to-ship groundwave communication case, the geometry and relative power levels will determine whether jamming is possible. The communicator can choose any frequency in the HF range but will probably choose

a low frequency (2-6 MHz) in the daytime and a high frequency (above 25 MHz) at night for LPI. This tactic will also defeat (in most cases) the distant jammer who relies on sky-wave propagation to deliver his energy because his signal will be highly absorbed by day and above the MUF at night. The success of the "nearby" groundwave jammer is a deterministic function of distances, power levels and frequency and can be estimated from ground wave propagation curves [for example Barrick 1970]. In general, the higher frequencies are attenuated more rapidly for a given increase in distance and therefore provide more protection from a groundwave jammer than the lower frequencies. For example, consider a 100 km communication path over a smooth sea. At 3 MHz the jammer must have a 3 db power advantage to be effective (J/S=0db) at a distance of 130 km from the victim receiver. At 30 MHz the jammer needs a 9 db power advantage to work from the same location.

6.0 Jamming Countermeasures

Two countermeasures to skywave jamming are diversity reception and adaptive null steering. The former approach takes account of the fact that skywave signals fade independently if the paths being monitored are sufficiently separated. Usually the scheme is employed to improve the S/N of the wanted signal in a fading environment; it has enjoyed success to counter ionospheric scintillation of SATCOM signals as well as HF communication signals. Its employment for mitigation of unwanted interference allows for excision of the jamming signal on each (separated) channel independently followed by a diversity combiner to derive any gain (against normal fading) which is still available. The worst case situation would be, of course, one for which the jamming signal and the communication signal are correlated. Fortunately this probability is remote unless the skywave paths are almost identical owing to the spatial variability of ionospheric propagation. If the jammer location were known it would be possible through propagation assessment to maximize the fading of the jammer and minimize the fading of the wanted signal.

7.0 Hearability Function: The First Step in Simulation

In section 5.3, it was indicated that the determination of an optimized location for a jammer depended upon a number of factors not the least of which was the set of frequencies available to the communicator to be jammed. The converse is also true if the jammer is to be thwarted.

The first step in analysis of this propagation war game is to contruct a "hearability matrix" for the range of frequencies available to both jammer and communicator. Hearability simply implies the availability ($\Gamma = 1$) or non-availability ($\Gamma = 0$) of signals as deduced from standard ray theory in the skywave case. For convenience we reference to the receiver terminal location (i.e., the victim of a jamming threat). For each frequency and receiver position we have

$$\Gamma_{ijk}(f;\lambda\phi) = \Gamma\left[B_j, R_j, M_k\right] \qquad (1)$$

where B_i is the set of bearings from the receiver to jammer (jammer path) or from the receiver to wanted transmitter (signal path), R_j is the set of ranges considered in both cases, M_k is the set of propagation modes available over both the jammer and signal paths, and the index L is binary corresponding to specification of either a jammer case or a signal case. In actual fact this matrix is continuous in B and R but it is convenient (and appropriate) to partition these functions. The situation is further

complicated if we allow another degree of freedom; i.e., a matrix of communication nodes. Ignoring this complication, handled easily by computer, we must regard the hearability matrix to be a function of time t (diurnal, seasonal, solar epochal) as well as a function of solar and geomagnetic activity. Thus we have

$$\Gamma^{\ell}_{ijk} = \Gamma^{\ell}_{ijk}\,(f;\lambda,\phi,\ t,s,K) \qquad (2)$$

where S is some suitable solar activity index (not necessarily sunspot number nor 10.7 cm flux) and K is the same suitable index of magnetic activity (not necessarilly the traditional K_p index). It is noteworthy that the dependence of upon λ and ϕ varies with the dynamic movement of various geophysical features such as the equatorial anomaly and the auroral oval and these in turn depend in a somewhat imprecise way upon S and K.

The apparent complicated form of makes the propagation tactics "war game" very interesting indeed and this diversity has certainly contributed to the myth described in section 5.0 which suggests that the operational use of propagation tactics is impractical and should be relegated to the "sandboxes" of the scientists. For one thing the solution to

$$\Gamma^{\ell}_{ijk}\,(f;\ \lambda,\ \phi,\ t,S,K) = 0,1 \qquad (3)$$

would involve a large computer, likely inappropriate for shipboard use, as well as a tested "model" of the channel. For another, the hearability is distorted by other parameters such as ducting, chordal mode propagation, above-the-MUF considerations, side-scatter and so on.

In addition, the definition of hearability itself is system-dependent to a certain extent. Clearly this is true at the boundaries near the LUF (lowest useable frequency) and the MUF (Maximum Useable Frequency), and it is also a factor in surface wave analysis. Ultimately there will be some degree of arbitrariness in the hearability defintions. In a computer simulation, for example, in which a pre-selected ionospheric model is used in conjunction with a ray-tracing algorithm, the computed rays for the skywave case depend critically upon the detailed structure (i.e., granularity) in the ionosphere and the selection of ray launch angles. (Of course, ray optics breaks down under certain conditions and caution should be used). Ultimately computer cost and time will dictate the precision of the hearability function. The accuracy of the function depends upon the efficacy of the model employed. Also it is worth reminding the reader that within the skip contour (a ray caustic) the hearability is defined to be zero. However, ray theory cannot allow for computation of signal strength at the skip distance and certainly within it. In reality the skip zone (or annulus between the skip contour and the ground wave "terminator") is slightly illuminated by scattering from irregular features and some radio energy is diffracted within the annulus.

8.0 Studies in Propagation Tactics

As indicated previously, Hayden [1979] and others have examined the properties of the HF channel as it relates to EW and propagation tactics. The most noteworthy practical applications have been developed by NOSC in conjunction with the PROPHET terminal [Rose, 1982; Argo and Rothmuller, 1981]. The work of Hayden was based upon raytracing through idealized model ionospheres (a superposition of Chapman profiles) whereas the NOSC organization and its contractors determine the basic parameters of propagation using the CCIR model for noise and simple models for the MUF and LUF which

have been developed under the PROPHET program over the years. Thus the NOSC approach circumvents the direct use of an ionospheric model. However, they have developed a ray tracing algorithm based upon a simulated ionosphere deduced from archives of oblique propagation data. Of particular interest in the current context is the NOSC CLASSIC PROPHET system which has been designed to support US Navy HFDF operations and the Tactical Prediction Module which has SIGSEC and COMSEC applications. The reader is referred to the report by Rose [1981] for a summary of the use of PROPHET for propagation tactics and EW applications.

Recently White and Wilson [1981] have concluded a study for the US Navy, the purpose of which was to examine fleet vulnerability to jamming in the Mediterranean and Indian Ocean zones. It is partially based upon earlier work by Coleman et al [1979] and White [1979] which is available in the open literature. This study performed for the US Navy by MITRE Corporation, made use of the program HFMUFES in its HF propagation simulations.

9.0 The approaches used by NRL

NRL has pursued several courses vis-a-vis propagation prediction technology. Statistical models have been examined to ascertain their validity to operational conditions but the most vigorous efforts have involved HF propagation evolution using update techniques. The update approach leads to a type of adaptive HF as distinct from the use of statistical (mean) models regardless of either their operational simplicity or computational elegance. NRL has employed topside sounder data as well as oblique bottomside sounder data to update models principally for use in HF frequency management. The greatest experience has been in the utilization of the output of the Barry AN/TRQ-35 chirp sounder as a path evaluator.

The basic approach to model update is simple. We start with a simple model of the ionospheric HF channel. Consider first the MUF which has a fairly well defined diurnal behavior and which we term a diurnal form factor or the zeroth order MUF estimate. The major component of ionospheric variability of the average diurnal term may be removed by excizing the bias (or d.c. term) between the model estimate (zeroth order function) and the actual function. This bias has been found to be several MHz in practice. This first order estimate of MUF is determined typically by a single 24-hour update, with the time of update judiciously pre-selected (based upon experience) to minimize the residual D.C. term in the diurnal variability. This update time, although variable, ranges between 0600-1200 LMT. For many data sets it has been discovered that the first order estimate of the MUF (which following update, should probably be called the MOF) is accurate to about 1 MHz or so in terms of temporal perishability over a 24 hour period. Furthermore, and more importantly, the results over a test path using the same bias-removing scheme appear valid over disjoint paths. The validity limits remain to be established but preliminary experimental results suggest that distances between ray path midpoints of as much as 1000 km will still allow for full removal of the MUF bias (d.c. term in the variability).

It has also been concluded from mid-latitude tests conducted during magnetically active periods that the temporal perishability problem increases. This is to be expected. We may regard this variability as a modification in the first order result which may be removed by more frequent updating. Practice has shown that the average update interval for maintaining an rms deviation of 1.0 MHz between the zeroth order model and the actual values of MUF was 3 hours.

9.1 The Data Sets used by NRL

NRL 4180 has participated in a number of excerises between 1980 and the present during which data has been obtained to test its update hypothesis. The first such test was conducted in conjunction with the TEAMWORK '80 exercise. More will be said about this in section 10. A list of operations follow:

TABLE 2

TEAMWORK '80	N. Atlantic	Sept 3-23, 1980
SURTASS 1	Mid-Atlantic	Feb. 15-23, 1981
POLAR SEA	Alaska	Apr 13-16, 1981
SOLID SHIELD	Mid-Atlantic	May 3-19, 1981
INDIAN OCEAN	Indian Ocean	Jul 25 - Aug 24, 1981
SURTASS II	Mid-Atlantic	Nov 10-22, 1981
GREEN TOAD	Mid-Atlantic/Caribbean	Mar 19-29, 1982

As can be seen in Figure 1 the solar activity during the 1981 tests (prior to SURTASS II) was high but variable. For a full discussion of these tests refer to a series of NRL reports [Uffelman, 1981; Uffelman and Harnish, 1981; Uffelman and Harnish, 1982] and a paper presented at IES '81 [Uffelman, 1982].

10.0 A Case Study

10.1 Background and Scenario Definition

For the purposes of our discussion, a case study will be developed drawing upon a set of data obtained from an oblique sounder net implemented during the NATO TEAMWORK '80 exercises which took place in September 1980. This net is shown plotted on the great circle map in Figure 2. During these exercises, BARRY AN/TRQ-35 transmitters were placed at Soc Buchan, Scotland (T_1); Kolsaas Norway (T_2); and Orland, Norway (T_3). The receiver was located on-board the USS Mt. Whitney, which was located off the coast of Norway as designated by an R in Figure 2. The path length from T_1 to R is approximately 830 km, T_2 to R is approximately 340 km, T_3 to R is about 104 km. The sounder net is located such that local time and universal time are the same.

Upon analyzing the data obtained during TEAMWORK '80, it was discovered that the quality of the data over the T_3 to R link was quite poor. Hence, to develop this case study only the T_1 and T_2 to R links will be considered. For this case study, suppose the ship desires high quality HF communications to Soc Buchen Scotland. In addition, suppose there is an adversary listening and/or jamming site located on a path equivalent to the T_2 to R link. Is it possible to employ some type of propagation tactic to neutralize the site at T_2 and still maintain message traffic over the T_1 to R link? In addition, is it possible to reliably employ these tactics as derived from computational assets? These questions will be answered for the particular scenario and geometry considered.

10.2 Data Analysis Explanation

To understand the case study, some discussion is required of the data we have drawn upon. Figure 3 gives an example of the type of data obtained from

this exercise. Although this particular example is not from the NATO Teamwork '80, it is exemplary of the form in which our data base is currently obtained. The TRQ-35 receiver yields a display of received frequency versus time delay (an oblique ionogram), as well as frequency vs. signal level. The ionogram is the lower portion of the display. At the top of the display is a plot of the receiver AGC as a function of frequency. This AGC plot may be used to infer a measure of received signal strength. This display is photographed using a polaroid camera. From data of this form, NRL personnel scaled three parameters. These are the maximum observed frequency (MOF), in this particular example labeled the maximum usable frequency (MUF); the lowest observed frequency (LOF), in this particular example somewhere near 2 MHz; and finally the band of optimum transmission frequencies (FOT band). For convenience, we define the FOT band as that band of frequencies which show high signal strength and no multi-path. Typically, the FOT band is located starting just below the point where O-X splitting converges. For the purposes of scaling data, the MUF is defined as the highest frequency at which energy reaches that receiver from the transmitter.

The data is scaled and a MUF-LUF-FOT plot is produced for the 24 hour period of interest. Figure 4 shows the diurnal plot produced by scaling a 24 hour period of data obtained from TEAMWORK '80 for the period of time between 0600 UT on September 18 thru 0600 UT on September 19, 1980. The upper trace is the MUF, the vertical lines show the FOT band, and the lowest trace is the LUF. Notice that in the neighborhood of midnight a sudden increase in the scaled maximum useable frequency occurs. Later, we will see that this is due to scattering, probably from auroral forms.

Figure 5 is the MUF-LUF-FOT plot for the data obtained from the Kolsaas Norway to Mt Whitney path. Note that there are times in this data set such that no FOT band is apparent. This is simply due to the fact that there is multi-path observed at all frequencies across the band as extracted from the ionograms. Also note that the Kolsaas path shows the increased MUF at night which is indicative of scattering which was observed. In order to investigate the applicability of computer models to assist the user to employ propagation tactics, a current widely used model, MINIMUF 3.5 developed by NOSC, was played against Mt Whitney data set, MINIMUF 3.5 is incorporated as the MUF algorithm of the NOSC PROPHET prediction system.

Figure 6 shows the difference between the measured maximum useable frequencies and the MINIMUF 3.5-computed MUF obtained over the Soc Buchan to Mt. Whitney path. The RMS error was found to be 3.83 MHz. This RMS error is commensurate with the advertised accuracy of the MINIMUF algorithm against larger data sets. Figure 7 indicates the model comparison against the data obtained over the Kolsaas Norway to Mt. Whitney path. Here we find an RMS error of 4.03 MHz in both this case and the previous case, much of the error appears to come from the scattering portion (nose-extension) of the data set. Since the MINIMUF 3.5 computer algorithm utilized for this comparison has no capability to predict scattering phenomena, we will remove this scattering so that we can compare the model directly with the symmetric propagation portion of the ionogram. In addition, we note that if the model were shifted to the right there would be a better match-up of the model with the scaled data. In order to establish a basis for the shift, the model sunrise and the data sunrise were matched . This requires a shift of the model to the right of approximately two hours. Further comparisons of the model and the measurements will also involve matching the model sunrise and sunset transmission with that of the data.

The next step taken was to force the model to fit the measured maximum useable frequency at one point in time for the Kolsaas path by varying the model's driving parameter (10.7 cm flux) to obtain the fit. The data period

selected was shortly after sunrise and the model predictions and data sets were forced into agreement at a single point during this period. Figure 8 illustrates the result of this operation. The maximum useable frequency derived from the sounder at 0600 UT was used to adjust the MINIMUF model. This is the bias-removal process by which the d.c. term in the ionospheric variability is excized (see Section 9.0) This adjustment, in turn, dictates an adjustment in the MINIMUF driving parameter which is 10.7 cm flux. A 10.7 cm flux of 250 was derived from this force fit and this parameter was then used to perform model calculations for the remainder of the day for the Kolsaas path as well as for the other path in our data set. This operation yielded an extemely good fit between data and revised model over the daylight period of the day, but a large RMS error occurred at night when scattering processes were encountered. Hence the RMS overall diurnal dropped down to only 2.87 MHz.

Next, the 10.7 cm flux, as derived from the Kolsaas path was applied to the model calculation of MUF for the Soc Buchan path. That result is shown in Figure 9. In this calculation, the 10.7 cm flux of 250 yielded a 1.64 MHz RMS error for the experimental path. Much of that error is noted as due to the scattering which occurs near midnight.

It was stated earlier that the MINIMUF algorithm used in this comparison has no capability to predict the occurrence of scattering pheonomena. Hence in order to make a comparison of the model with the diurnal variation of the channel, the scattering component of the data was removed. Figure IO illustrates how this was done. Around midnight, a scattering component appears at a higher frequency than that of the normal ionogram. One can see the normal O-X splitting, which is due to the non-scattered component of the trace on the ionogram. Using this information, the data was re-scaled for the the period during which scattering was evident to exhibit only the symmetric propagation portion of the data ,and following this process the model comparison was repeated over the two paths of interest. These comparisons are shown in Figures 11 and 12. Figure 11 is data from the Kolsaas, to Mt. Whitney path which in this particular data set was used as a control from which the update was extracted. Note that the RMS error between the model and the actual data has dropped to 0.85 MHz. Figure 12 shows the comparison where the scattering has been removed over the Soc Buchan to Mt. Whitney path. Here, however, the update was obtained from the control path (Kolsaas Norway to Mt. Whitney). With the scattering removed, the RMS error between the MINIMUF computation of the MUF and the actual measured MUF was again 0.85 MHz. The update has therefore yielded a particularly good fit of the simple MINIMUF model to the actual measured MUF.

A point has been reached in our development of the case study where we have shown with a limited data set, that an updated computer algorithm, in this case MINIMUF 3.5, was successful in producing an accurate estimate of the HF channel MUF variation over two separate paths. It should be noted that utilization of the longer path (Soc Buchan to Mt. Whitney) as the control from which the update is derived yields precisely the same result that is shown in this example.

10.3 EW Scenario

With the above information in mind, we will simulate the example scenario mentioned in section 10.1 where propagation tactics are employed against an adversary. We will show, at least in this case, that use of an updated model will allow MUF selection for establishment of a reasonable HF communications

link as well as deny information to the adversary. In addition, we will show that care must be taken since the computer calculations get us into trouble if update is either not performed on the basic computer model or if it is done improperly.

As a starting point consider Figure 13. In this figure we have simply overlayed the actual MUF, LOF and FOT scalings for the two paths of Soc Buchan Scotland to the receiver and Kolsaas Norway to the receiver. The larger MUF's are associated with the longer path to Soc Buchan, the lower MUF's are associated with the shorter Kolsaas path. Using this scaled data as a guide, there is a set of frequencies available which are below the maximum useable frequency of the desired path for communication, but above the maximum useable frequency of the adversary path. Hence, for a large part of the day there is the capability to employ a propagation tactic by using the natural variation in the HF channel. In the evening when scattering occurs, the scattered mode allows energy to reach the adversary. Whether or not this energy is intelligible and information can be derived from it, is another question however. When the scattering component is removed, we will show that for most of the 24 hour period considered, frequencies can be selected to actually deny the adversary information by the mode which is based on symmetric propagation. It is our premise that if this measured diurnal variation of the channel can be modeled accurately, one could use the computer to pick these desirable frequencies. In fact, for this particular example, this will be shown to be the case.

To illustrate what can happen if the channel is not modelled precisely, consider Figure 14. Here we have overlayed the earlier examples of the difference calculation between the un-updated MINIMUF 3.5 and the actual MUF variation. When a model of MUF is used to select optimum communication frequencies, a value of 0.85 of the MUF is typically sought. Using this recipe we notice that if the model had been used to select desireable frequencies to the Soc Buchan terminal, one would utilize frequencies which are squarely in an optimum band for the adversary to receive the information. Hence, the tactician who is attempting to employ this tactic might feel secure that his information is being denied to the adversary but in fact the adversary actually has clear reception of the information. In addition, the tactician would be working at a frequency somewhat lower than the most desired frequency for maximum communication efficiency to the terminal of interest and hence would suffer from a reduced S/N ratio assuming fixed power of transmission. This further enhances the reception of the information by the adversary.

Figure 15 indicates what would happen if the model update was employed. This figure is an overlay of the difference calculations shown in earlier figures for the updated model. Notice that even with the scattering included, the model update would allow the tactician to pick frequencies above the adversary MUF and near the band of optimum frequencies for the desired communication channel for the majority of the day. At night, when scattering occurs, this same tactician would be selecting frequencies for which scattering would allow the adversary to receive some energy. However that energy is not very intelligible due to the multi-path effects of the scattering.

When the scattering is removed we see a quite different picture. Again the tactician can now utilize the model update as obtained from the computer to pick frequencies for almost a total 24 hour period to deny the adversary information over modes which could yield intelligible information. This is shown in Figure 16.

The example we have employed suggests that the propagation tactic to deny information to an adversary is viable. In addition, if that same adversary were attempting to jam the reception of messages from the Scotland terminal to the Mt. Whitney, skywave jamming would have been impossible for the adversary since the frequencies selected for communication would have been above the maximum useable frequency of the jammer to the receiver.

In conclusion, we have attempted to show in this case study that accurate knowledge of the HF propagation channel can allow a tactician to employ methods to optimize his use of HF communications against an adversary. These studies are in their initial phases and further work is continuing.

Conclusion

The need to consider the HF channel from the point of view of EW propagation tactics is well known and currently there exist several techniques for examining HF vulnerabilities to jamming, HF jam avoidance and kindred topics from a statistical point of view. The central point examined in this paper relates to the advantage which will accrue in the realm of propagation tactics if propagation (or ionospheric) models are updated in real time. An objective system has the functional flow illustrated in Figure 17. The real time assessment function, which is key to the whole hypothesis, is driven by a basic channel prediction function (perhaps of the climatological type) but is modified by geophysical update parameters embodied in the so-called forecasting function and by a remote sensing capability such as an oblique sounder. This information, together with corollary information concerning properties of the threat, is used to develop plans and EW action through the propagation tactics module on the flow diagram. The key ingredients to successful prediction are depicted in Figure 18.

NRL is currently testing the hypothesis that real-time updates of the ionosphere propagation channel will lead to an operationally viable procedure for real time HF channel property specification. It is argued that the hypothesis, if generally true, will address major problems having importance for EW, HFDF/HFTDOA, COMSEC/SIGSEC, and related areas as well as communication frequency management. In addition it may have application in the OTH-Radar arena but this discipline has not yet been examined.

Acknowledgements

The experimental effort embodied herein is due to a large number of dedicated NRL scientists, engineers and technicians; the work of L.O. Harnish is singled-out as being particularly noteworthy. The authors would also like to acknowledge the suggestions and comments of Dr. F.O. Fahlsing of the Information Technology Division at NRL. This work was supported by NAVELEXSYSCOM and NAVMAT. Guidance in the total effort has been provided by H. Fiegelson and CAPT W. MacLaine of the Office of Command and Control, U.S. Navy.

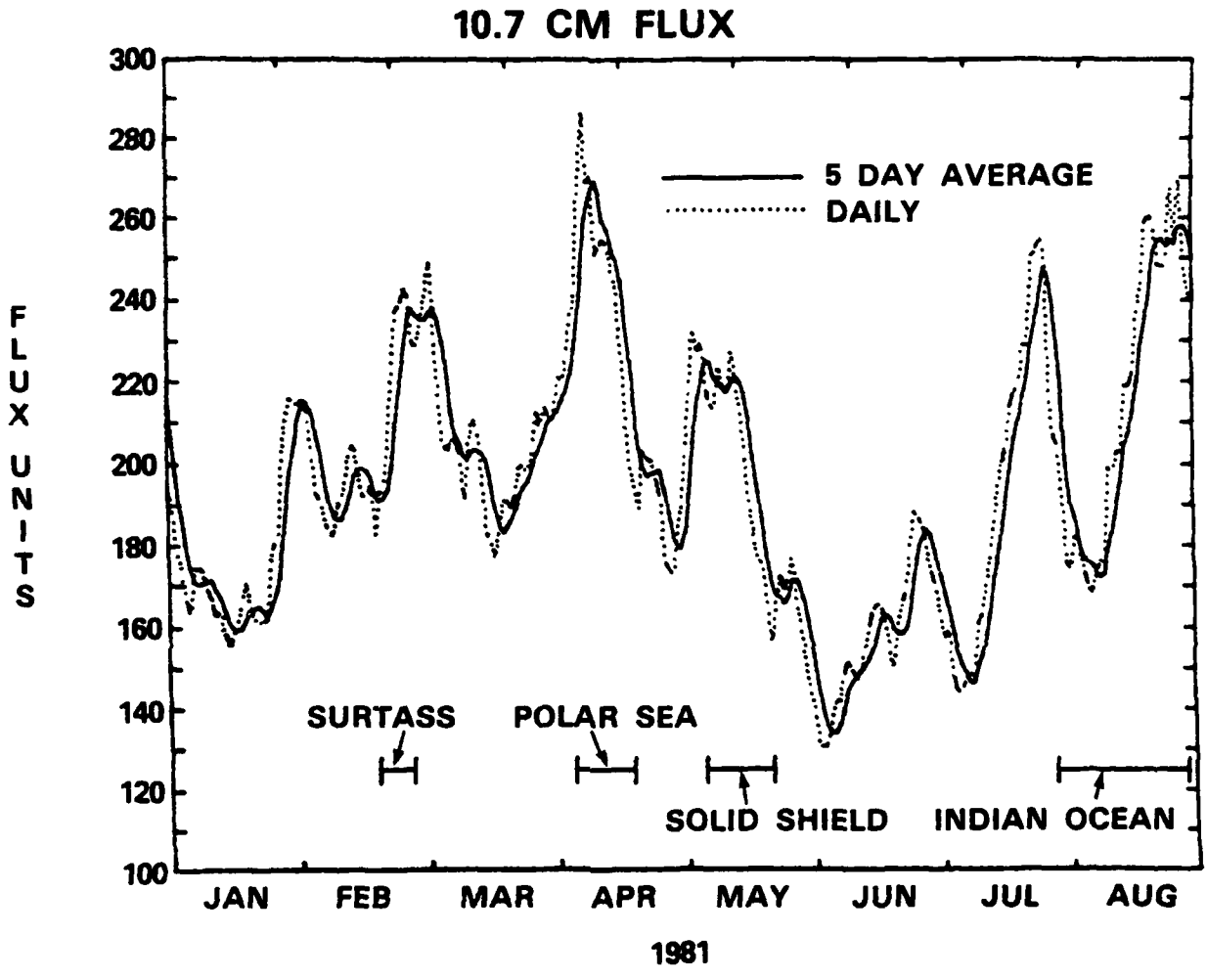


Fig. 1 — Solar background for 1981 operations

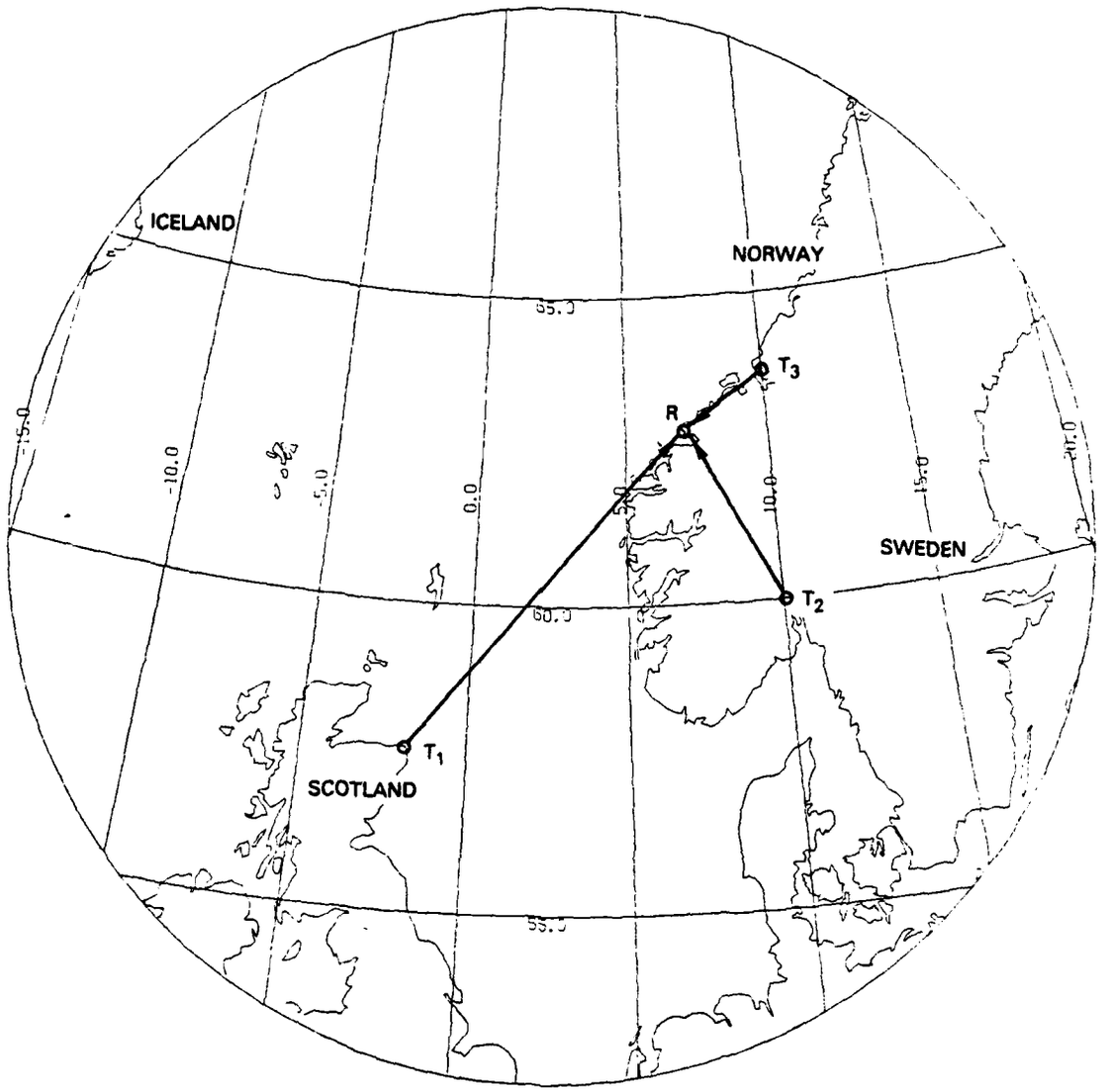


Fig. 2 — NATO TEAMWORK 280 experimental configuration oblique sounder net 18-19 Sept 1980

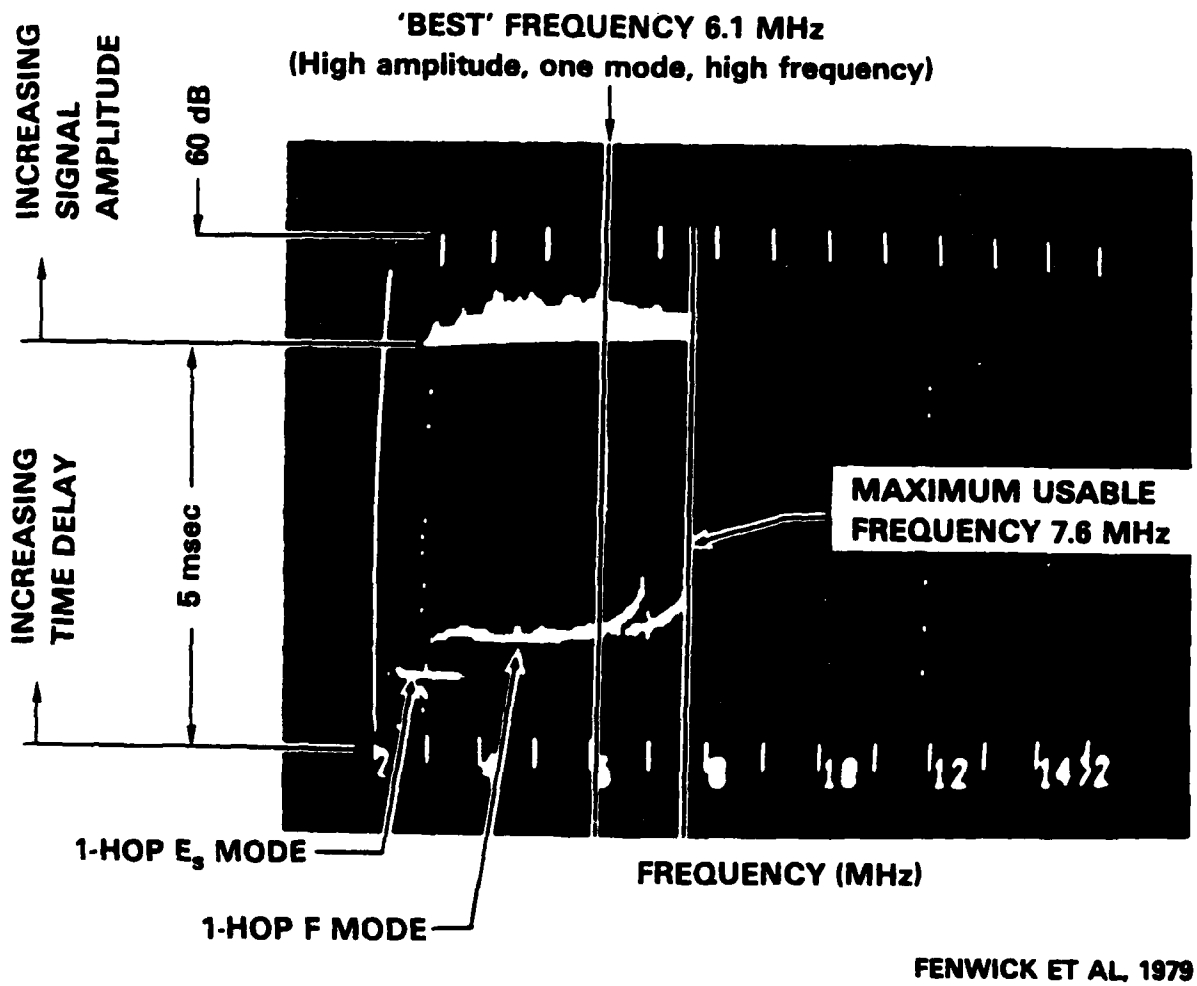
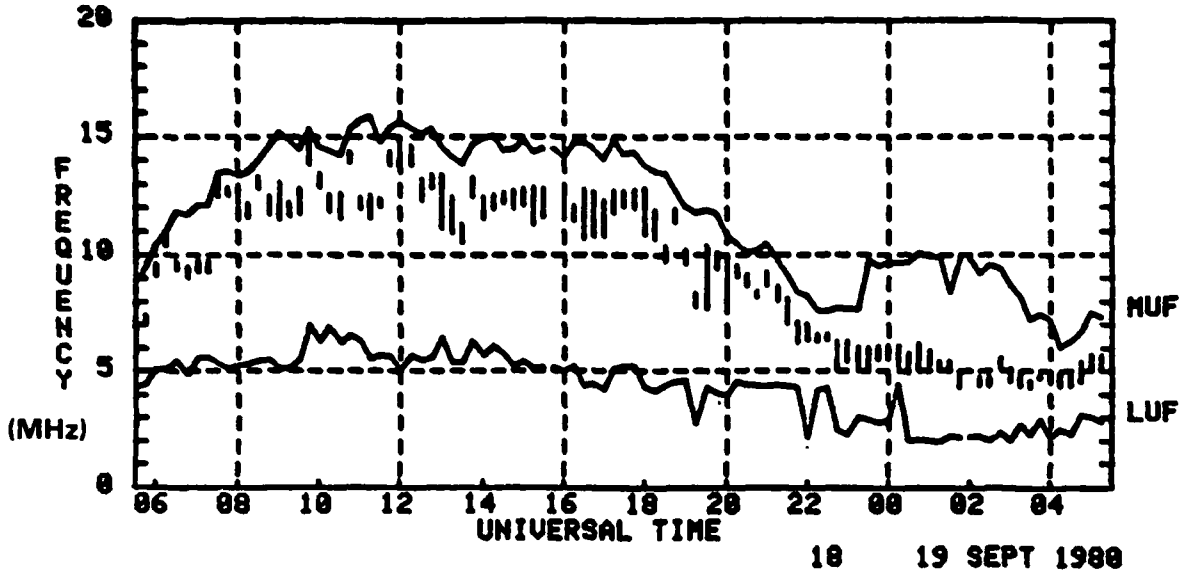


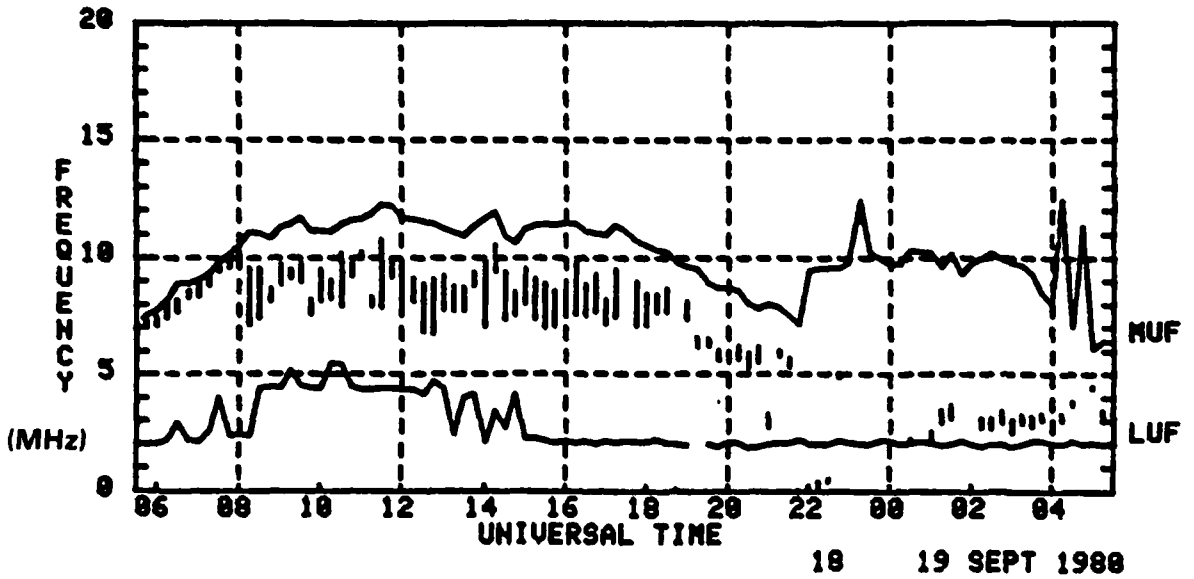
Fig. 3 — Annotated sounding from the chirp sounder



TRANSMITTER:
SOC BUCHAN, SCOTLAND
57.28N,1.58W

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

Fig. 4 — Actual MUF-LUF-FOT data from TRQ-35



TRANSMITTER:
KOLSAAS, NORWAY
60.02N,10.38E

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

Fig. 5 — Actual MUF-LUF-FOT data from TRQ-35

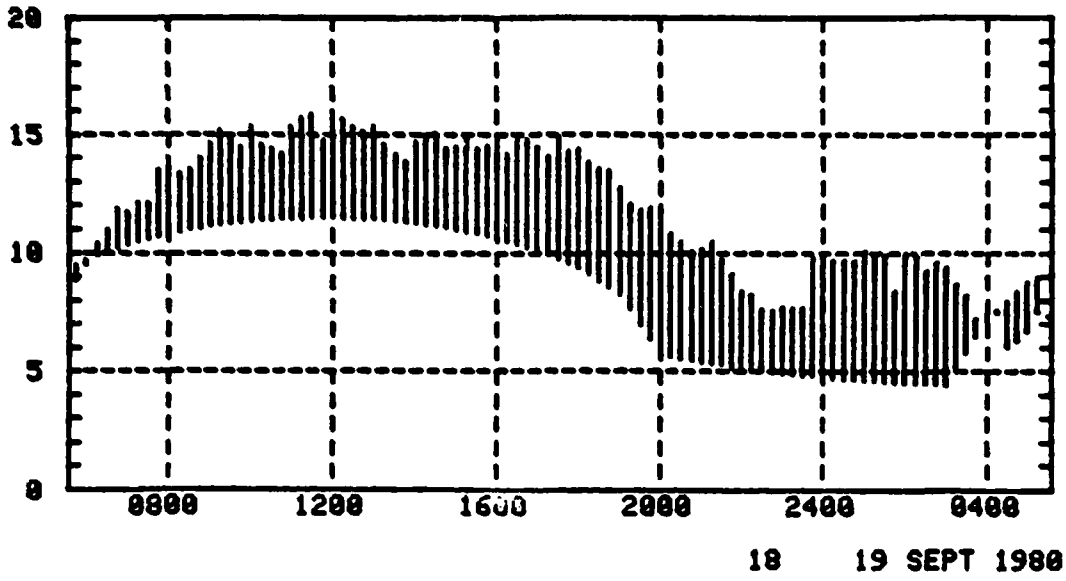


Fig. 6 — Difference between model and actual MUF

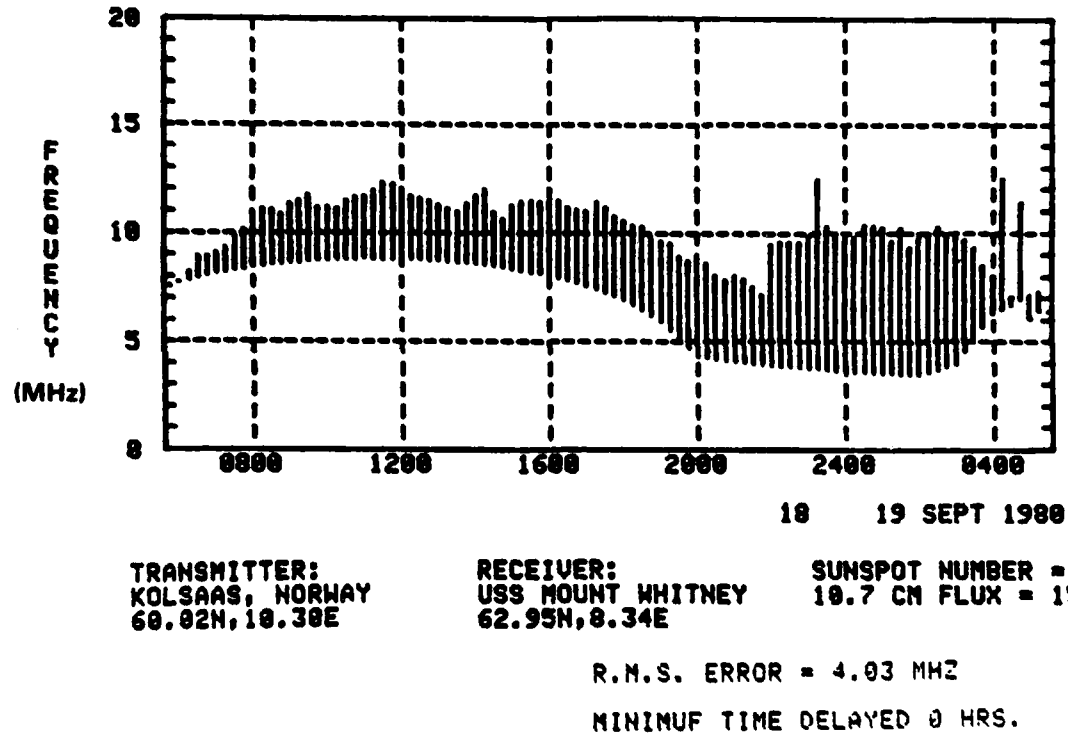
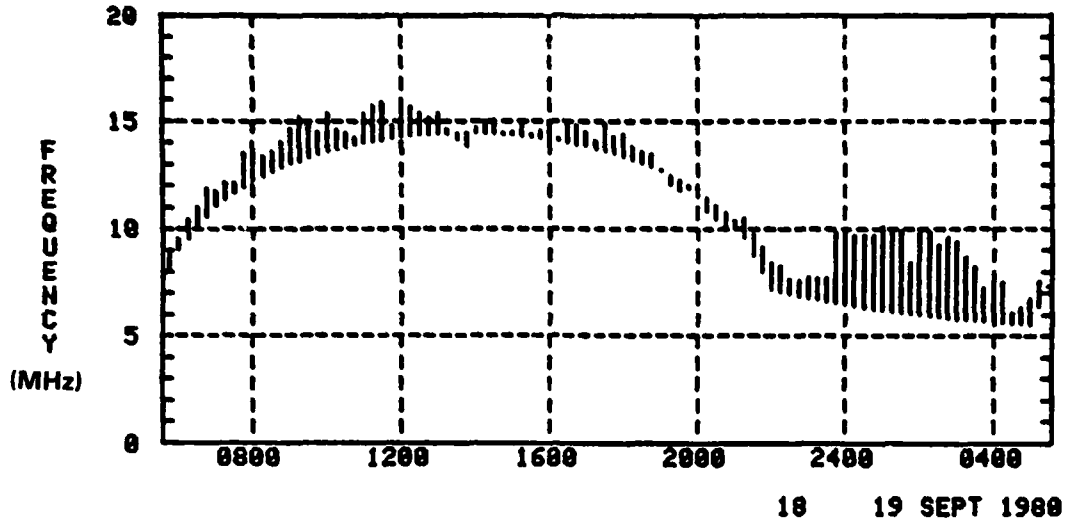


Fig. 7 — Difference between model and actual MUF



TRANSMITTER:
SOC BUCHAN SCOT
57.3N, 1.5W

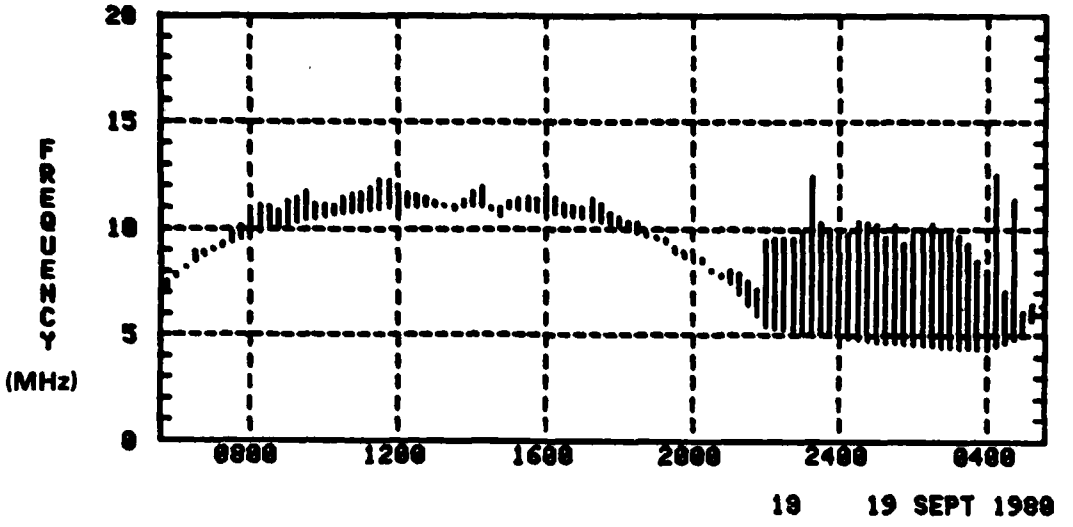
RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 205
10.7 CM FLUX = 250

R.M.S. ERROR = 1.64MHZ

MINIMUF TIME DELAYED 2 HRS.

Fig. 8 — Difference between updated model and actual MUF



TRANSMITTER:
KOLSAAS, NORWAY
60.0N,10.3E

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 205
10.7 CM FLUX = 250

R.M.S. ERROR = 2.87 MHZ

MINIMUF TIME DELAYED 2 HRS.

Fig. 9 — Difference between updated model and actual MUF

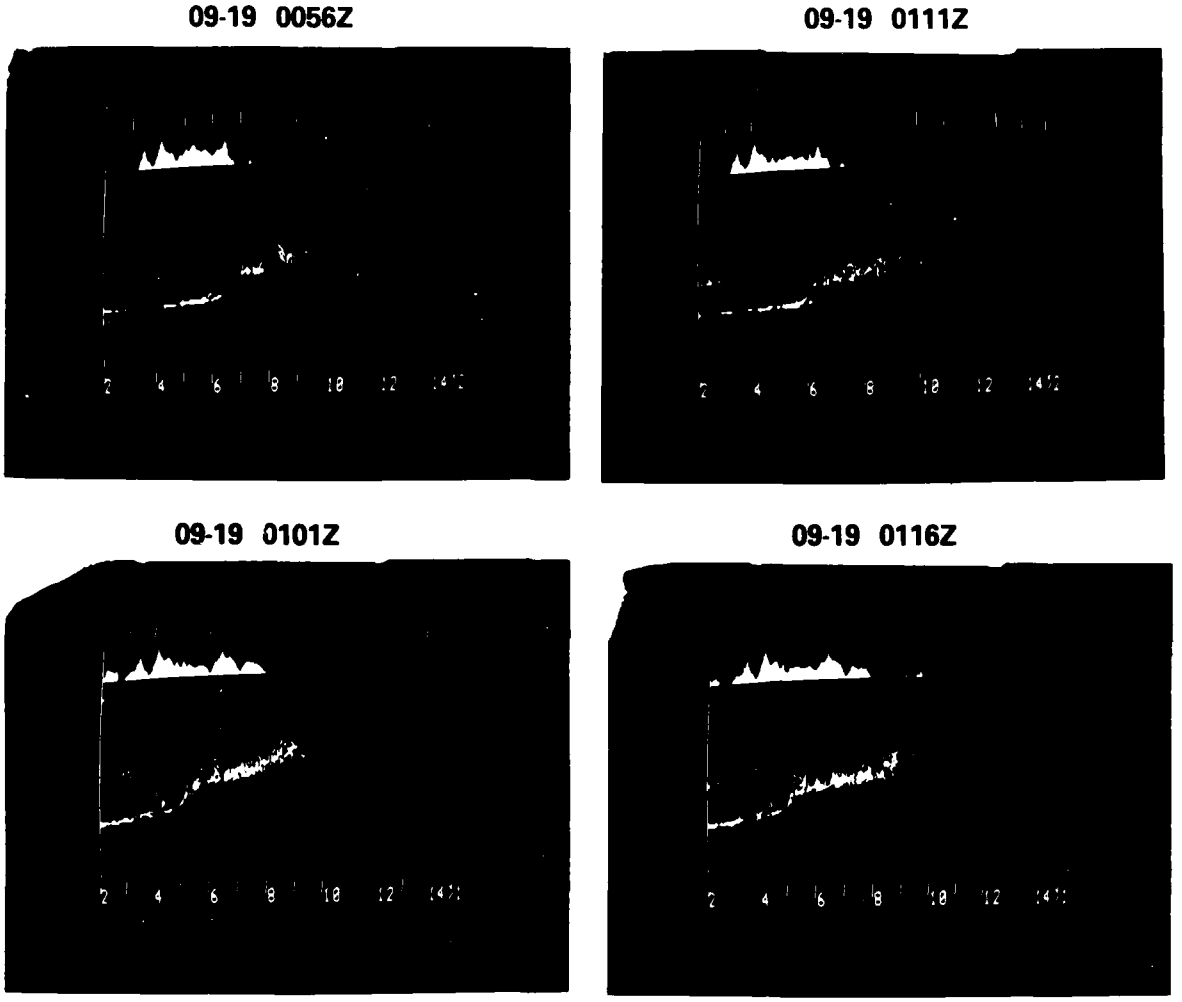
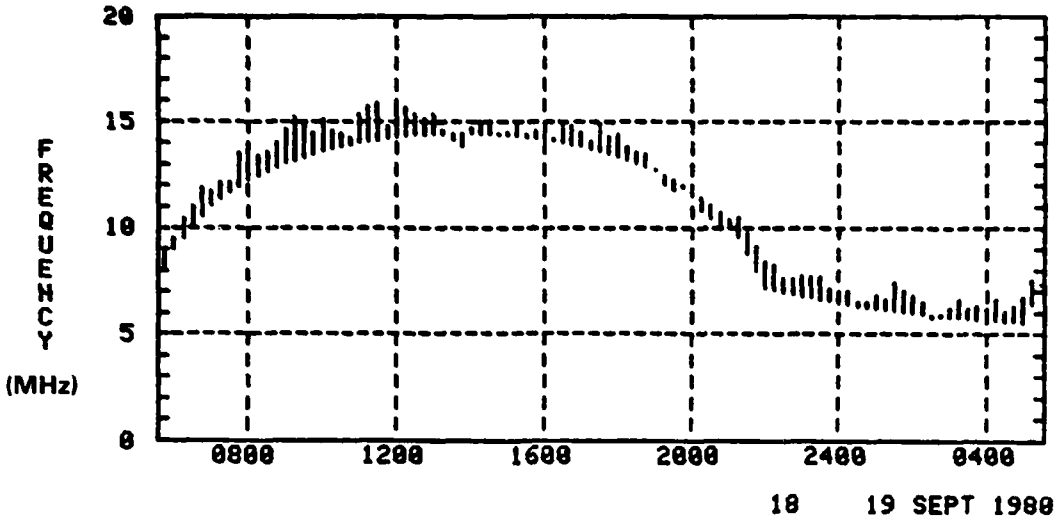


Fig. 10 — Oblique soundings showing extended MUF (nose extension)



TRANSMITTER:
SOC BUCHAN SCOT
57.3N, 1.5W

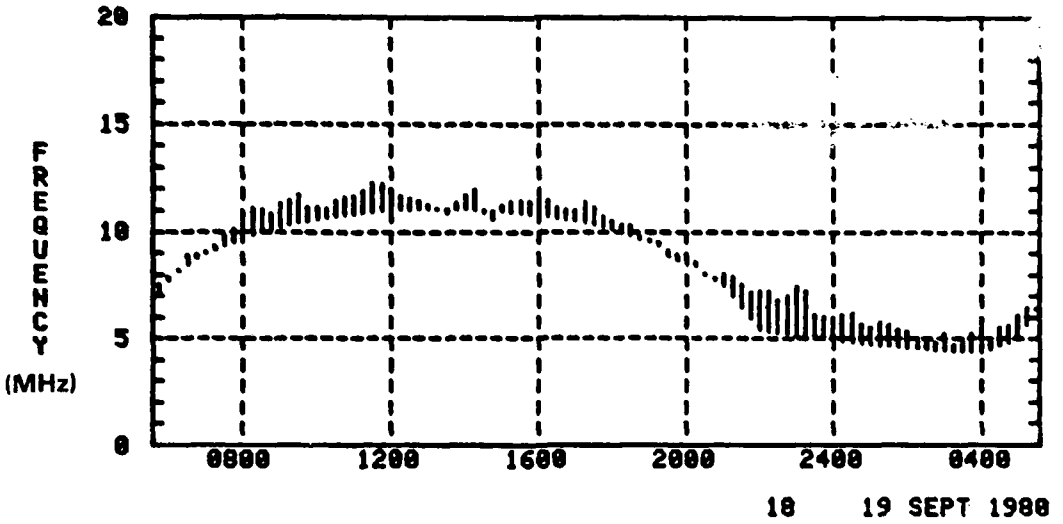
RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 205
10.7 CM FLUX = 250

R.M.S. ERROR = 0.85MHZ

MINIMUF TIME DELAYED 2 HRS.

Fig. 11 — Difference between updated model and actual MUF (no nose extension)



TRANSMITTER:
KOLSAAS, NORWAY
60.0N,10.3E

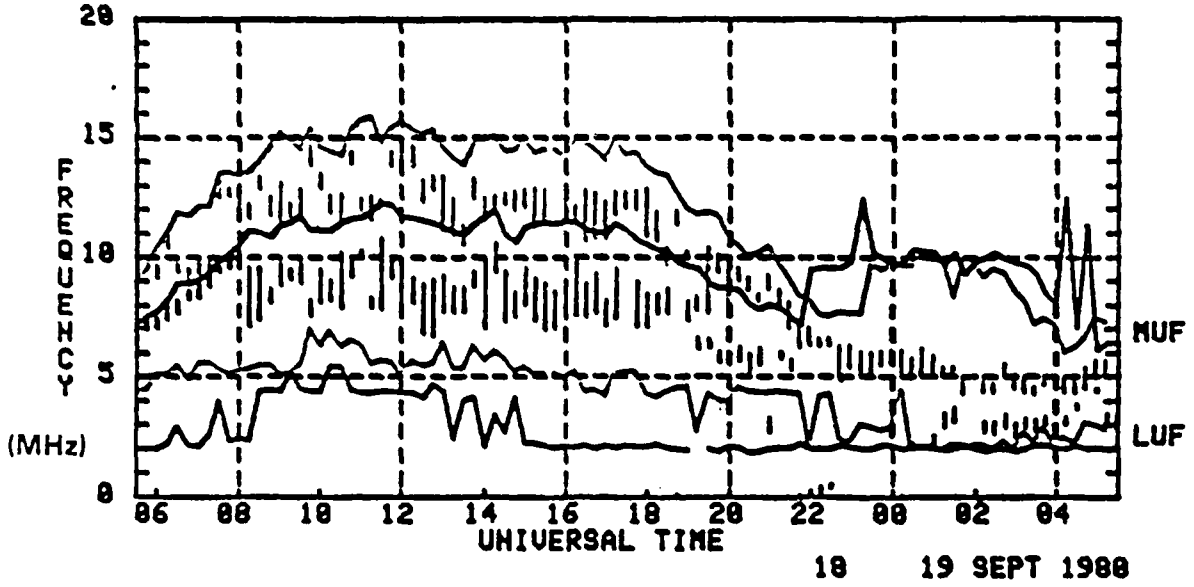
RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 205
10.7 CM FLUX = 250

R.M.S. ERROR = 0.85MHZ

MINIMUF TIME DELAYED 2 HRS.

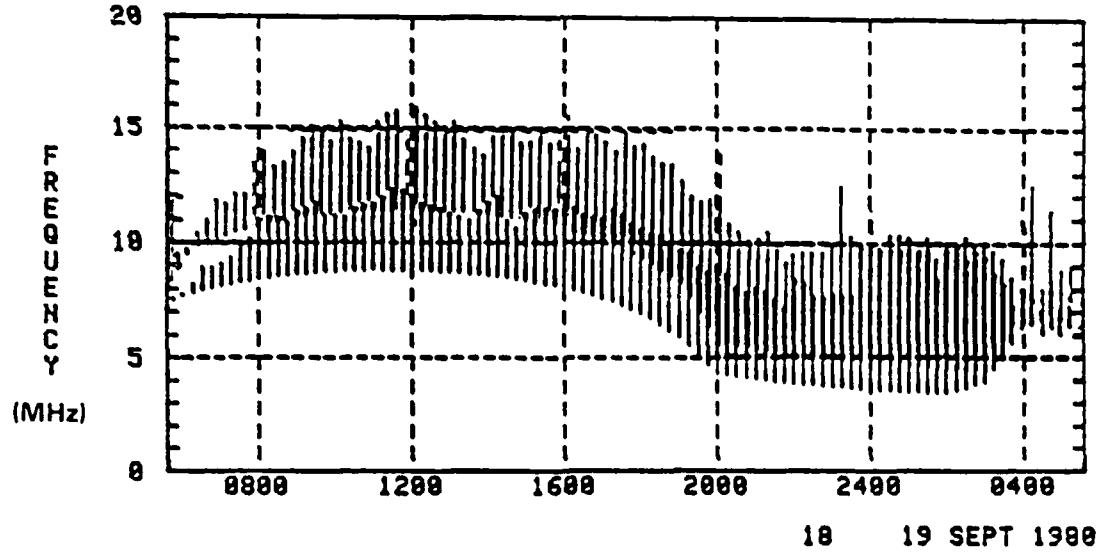
Fig. 12 — Difference between updated model and actual MUF (nose extension removed)



TRANSMITTERS:
SOC BUCHAN SCOTLAND
KOLSAAS, NORWAY

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

Fig. 13 — Actual MUF-LUF-FOT data

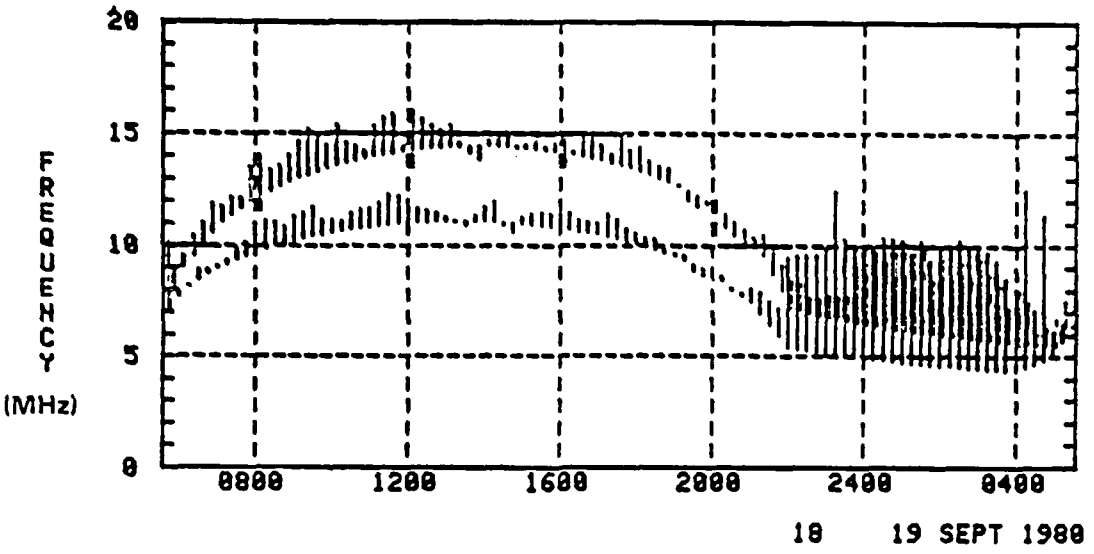


TRANSMITTERS:
SOC BUCHAN SCOTLAND
KOLSAAS, NORWAY

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 112
10.7 CM FLUX = 156

Fig. 14 — Actual model vs data difference or why accurate model is needed

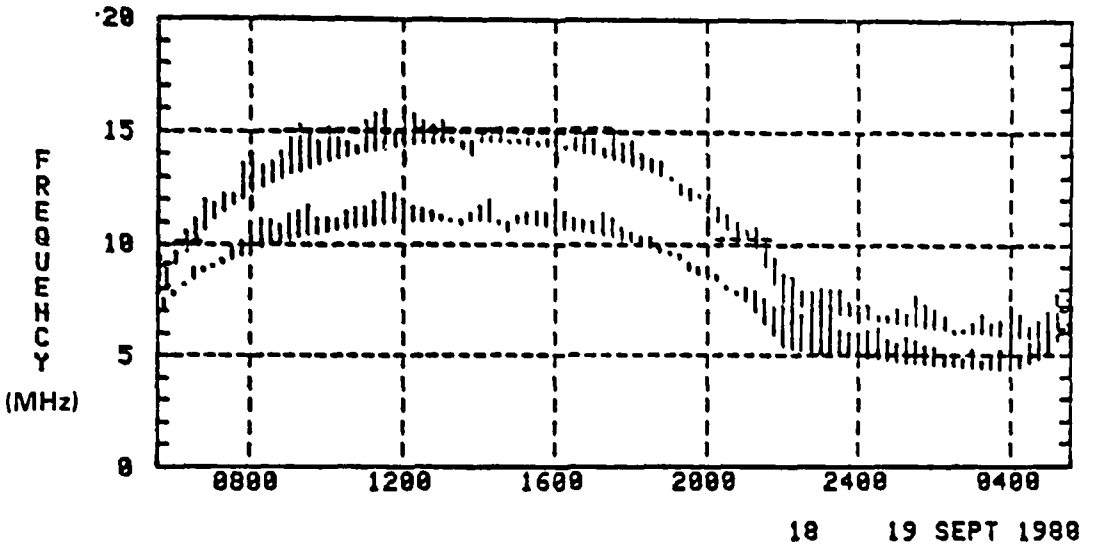


TRANSMITTERS:
SOC BUCHAN SCOTLAND
KOLSAAS, NORWAY

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 205
10.7 CM FLUX = 250

Fig. 15 — Updated model vs actual data or what reliability can do



TRANSMITTERS:
SOC BUCHAN SCOTLAND
KOLSAAS, NORWAY

RECEIVER:
USS MOUNT WHITNEY
62.95N,8.34E

SUNSPOT NUMBER = 205
10.7 CM FLUX = 250

Fig. 16 — Updated model vs actual data (no scattering)

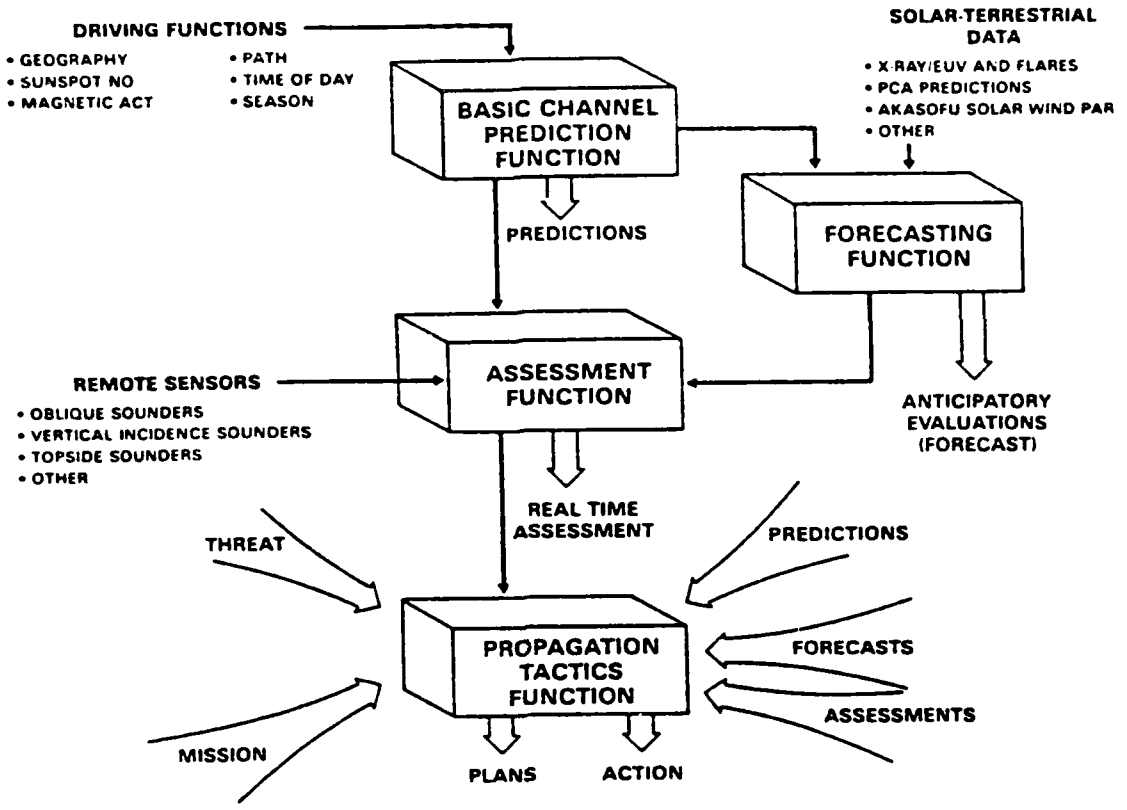
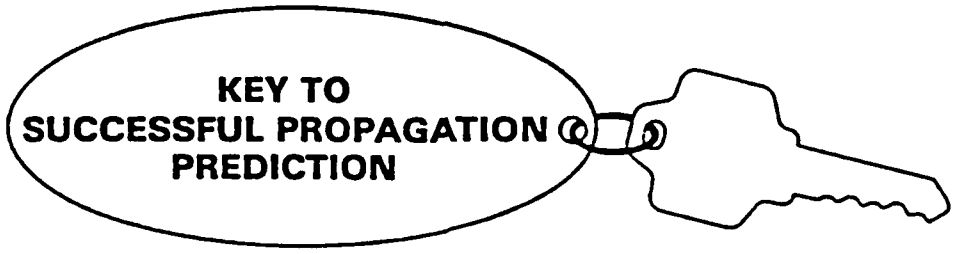


Fig. 17 — Candidate objective prediction, forecasting, and assessment system



- A MORPHOLOGICAL MODEL CAPABLE OF REAL-TIME UPDATE
- A REMOTE SENSING TECHNIQUE WITH EFFICACY
- A C^3 SYSTEM TO TIE THE OPERATION TOGETHER AND PROVIDE INFORMATION TO THE USER

Fig. 18 — Propagation tactics

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